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# (54) Semiconductor thermal neutron detector and thermal neutron detection method

(57) In order to detect thermal neutrons, a semiconductor device such as a diode or a DRAM is provided with a region 10 doped with nuclei having a large capture cross section for thermal neutrons, such as the $^{10}B$ boron isotope. The interaction of the thermal neutrons (30) with the $^{10}B$ isotope produces an alpha particle and a lithium nucleus (12) which can be detected. By reverse-biasing (7) a diode, the current produced by the motion of the fragments can be detected (8). Alternatively, any alpha particle detector can be used with an appropriate configuration of selected high thermal neutron capture cross-section materials to detect thermal neutrons.

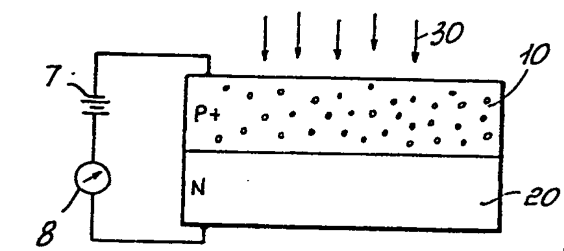


Fig. 1a

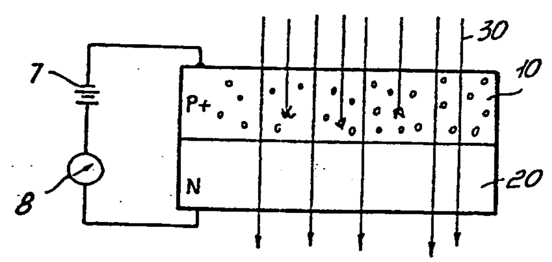


Fig. 1b

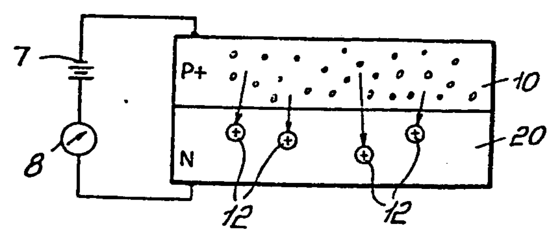


Fig. 1c

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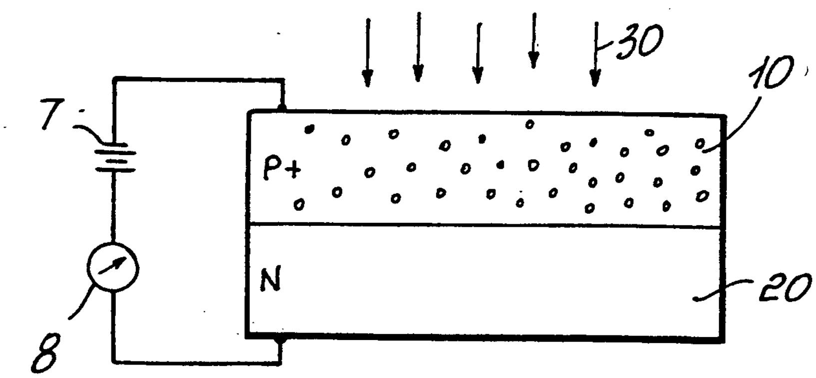


Fig. 1a

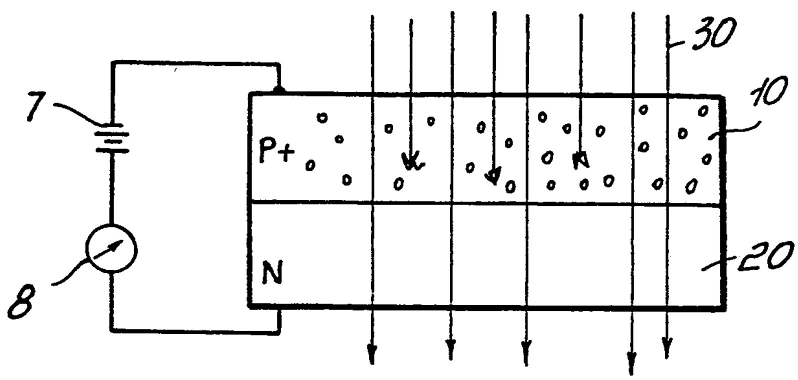


Fig. 1b

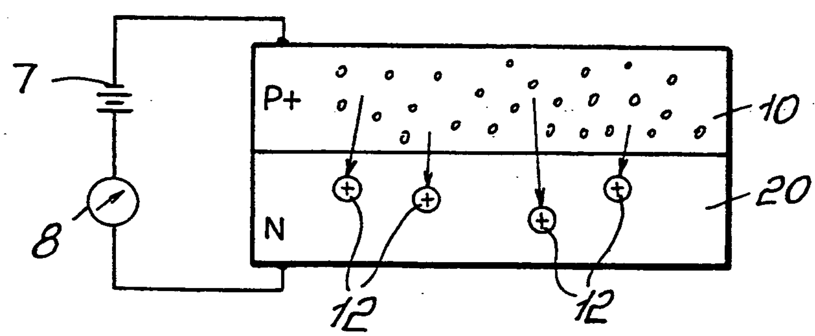


Fig. 1c

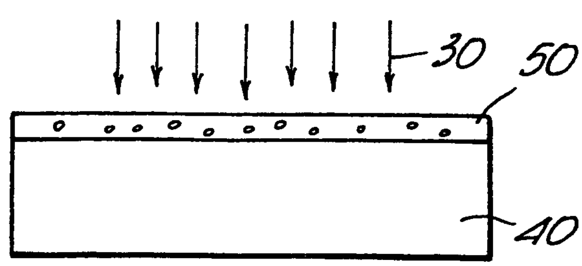


Fig. 2

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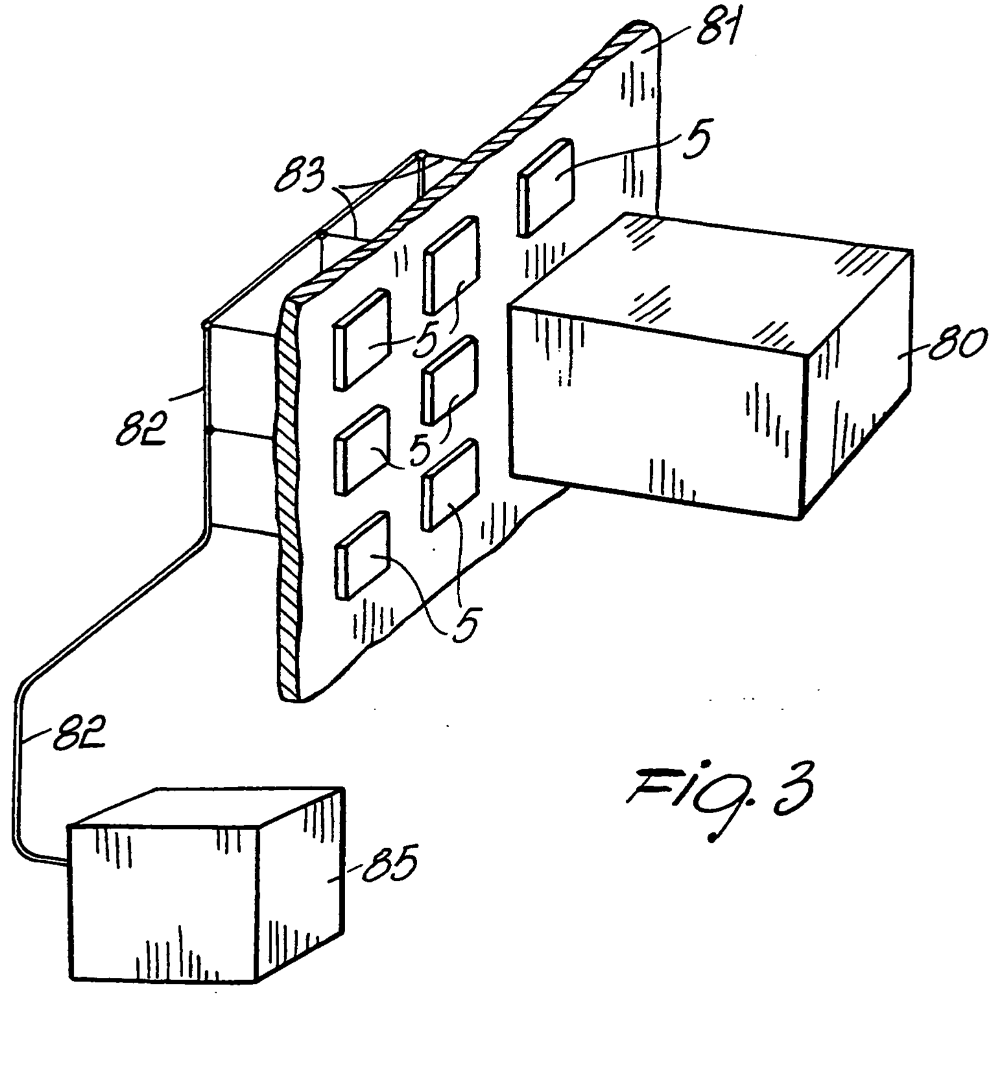


Fig. 3

SPECIFICATION

**Semiconductor thermal neutron detector and thermal neutron detection method**

This invention relates generally to detection of radiation and method of radiation detection and, more particularly, to the detection of thermal neutrons by a semiconductor diode and to a method for detecting thermal neutrons by a semiconductor diode.

It is generally known in the related art to use semiconducting PN type junctions to detect radiation. Photodiodes are widely employed in applications where a response to incident electromagnetic radiation is required. Similarly, silicon devices are so sensitive to ionizing radiation that in typical applications, effort is expended to reduce the radiation sensitivity. The PIN diodes can use ionizing radiation in applications for detection of X-rays and gamma rays, extensions of the electromagnetic spectrum. Finally it is known that alpha particles (the $^4He$ nuclei) can be detected by semiconductor devices and, particularly, dynamic random access memories.

However, the detection of thermal neutrons has remained a problem. For more energetic neutrons, the inelastic scattering (or radiation damage) can be used as a detection phenomenon or technique. However, for thermal neutrons, the lack of charge and the lack of sufficient kinetic energy make this radiation much more difficult to detect.

It is therefore the task of the present invention to provide a radiation detector and method of radiation detection capable of detecting thermal neutrons.

The aforementioned task is attained by a semiconductor thermal neutron detector, characterized in that it comprises at least one layer including a high concentration of P type dopant atoms for interacting with thermal neutrons and producing nuclear fragments as well as nuclear fragments detection means associated with said at least one layer. According to a preferred embodiment of the invention, a P+,N or N+,P, silicon diode, reverse-biased, with boron doping is provided, wherein the thermal neutrons impinge on the boron isotope type of nucleus which has a large reaction cross section, with the resulting decay into fragments of the nucleus. The ionized decay products cause or generate a net current when they cross the depletion zone of the diode, and a current can consequently be detected.

The thermal neutron detectors can be configured in an array around a thermal neutron flux or to localize the neutron flux. Similarly, when the first poly-silicon layer of N-channel dynamic random access memory elements are similarly doped with appropriate nuclei, the fission products of the resulting nuclear decay permit a space and time detection process by the random access memory control circuits.

The invention further relates to a method for detecting thermal neutrons, which is characterized in that it comprises an array of semiconductor devices, each device of said array having means for capturing said thermal neutrons and for generating a current resulting from the capture of said thermal neutrons, and sensing means for sensing the current generated by each device of said array resulting from the entering of thermal neutrons into each said device of said array.

The foregoing and other objects, features and advantages of the invention will be apparent from the following, more particular, description of the preferred embodiments of the invention as illustrated in the accompanying drawings.

*Figures 1a, b,* and *c* illustrate schematically a preferred embodiment of the present invention;

*Figure 2* is a generalized schematic diagram of the invention using an alpha particle detector to detect thermal neutrons; and

*Figure 3* is a schematic diagram showing the use of an array of detectors of the instant invention to monitor thermal neutron flux from a thernal neutron source.

Referring to Figure 1*a*, the semiconductor PN junction of the present invention is illustrated schematically. The PN junction consists of a P+ region 10 and an N region 20. The P+ region 10 is heavily doped with boron atoms. A flux of thermal neutrons 30 impinges upon the device, but most importantly on the boron-doped P+ region 10. The P+, N diode has a reverse bias voltage source 7 coupled thereto and a current detector 8 is included in the circuit.

Referring to Figure 1*b*, members of the impinging thermal neutron flux interact with certain of the boron atoms and nuclear reactions take place at sites illustrated by terminated flux lines in the figure. A majority of the thermal neutron flux proceeds through the diode structure without appreciable interaction.

Referring to Figure 1*c*, the decay fragments from the nuclear reaction are typically of sufficient energy to move through the material. This motion will cause ionization as the relatively weakly bound electrons are stripped from the moving nucleus. A portion of these ionized fragments 12 are brought to a halt in the N region of the diode, for example, through inelastic collisions. Silicon semiconductor devices are generally sensitive to ionizing radiation which is usually considered to be a weakness in certain applications, but not in the applications proposed herein. Technical publications that point out the ionization sensitivity of certain silicon devices are authored by R. Nowotny and W.L. Reiter, Nuclear Instrumentation Methods *147*, 477 (1977); *153*, 157, (1978). The applicants of this application have published an article in Nuclear Instrumentation Methods *169*, 125 (1980) relating to the sensitivity of dynamic random access memories (RAM) as alpha particle detectors.

Referring to Figure 2, a generalized thermal neutron detector according to the present invention is shown. An alpha particle detector 40 is shown in this figure. Deposited on the surface of the alpha particle detector is a thin layer of material 50 including nuclei such as $^{10}$Boron which have a relatively large capture cross section for thermal

neutrons. The interaction of the flux of thermal neutrons 30 from a thermal neutron source (not shown) with the $^{10}$Boron nuclei will result in alpha particles (and Lithium) being formed by virtue of the interaction formula shown below. The thus formed alpha particles impinge on the alpha particle detector 40 which provides an indication of the pressure of thermal neutrons.

Referring to Figure 3, the use of the various above described thermal neutron detectors of the instant invention to monitor neutron flux from a positive or potential thermal neutron source 80 (such as a nuclear reactor), is shown. A portion of an array of thermal neutron detectors 5 of one or more of the various above described thermal neutron detectors of the instant invention are shown mounted on a support or wall 81 which is shown with parts broken away. The thermal neutron detectors 5 are preferably located in an array surrounding the thermal neutrol source 80 (only one wall of which is shown for illustrative purposes) to provide an indication of the presence of thermal neutrons outside of the thermal neutrons source 80. The thermal neutron detectors 5 can include the apparatus or device of Figure 1 (*a, b, c*) or Figure 2 or any one or more of the other devices described herein and further include a current signal conductor 83 for transmitting the current generated by each of the detectors 5. Conducting bus 82 transfers the current status information from each of the thermal neutron detectors 5 to a neutron flux analyzer 85. In analyzer 85, the status information is assembled and thereby communicated in an appropriate manner.

The diode PN junction (formed by the P+ region 10 and N region 20) see Figures 1*a,b,c,* can be prepared using the techniques of local oxidation of silicon. This would be a planar type diode device which would have a P+ region located in an N region for a $P^+$, N diode device or an $N^+$ region located in a P region for an $N^+$,P diode device. These devices can be formed using implantation or diffusion techniques. In the case of an $N^+$,P diode device for use as part of a thermal neutron detector in accordance with this invention, it is preferable to dope the P field region with $^{10}$Boron atoms or nuclei and to implant $^{10}$Boron atoms or nuclei into a portion of the oxide layer located above the active region of the $N^+$,P, diode device. These diodes have a very low reverse current. Technical support for the low reverse current characteristics of $P^+$,N or $N^+$,P conventional diodes obtained by local oxidation of silicon is found in the technical publication by L. Baldi, G.F. Cerofolini and G. Ferla in the Journal of the Electrochemical Society *127,* 164 (1980). A typical value of current for a diode of one square centimeter with a reverse bias of 15V is of the order of 100 pA. Even large area diodes, with an area of ten square centimeters, will have negligible noise. Such diodes are good detectors of the alpha particles which are, in fact, helium nuclei. The current detector 8 shown in Figures 1*a,b,* and *c* is used to detect current across the diode.

Referring once again to Figures 1*a*, 1*b*, and 1*c* (illustrating the $P^+$,N diode), when a thermal neutron traverses the $P^+$ region of the diode, it will interact with a capturing boron (A=10), $^{10}$B, nucleus. The $^{10}$B nucleus (constituting approximately 19 percent of the natural boron) has a relatively high capture cross section (approximately 4000 barns) for thermal neutron capture. The reaction is as follows:

$$^{10}B + n = {}^{7}Li + {}^{4}He$$

where B is Boron, n is a (thermal) neutron; Li is Lithium and He is Helium. The equation is interpreted as the boron (A=10) nucleus plus a (thermal) neutron (A=1) produces a lithium (A=7) and an alpha particle (A=4) where (A) is the nucleon number. Either the alpha particles or the ionized or charged lithium nuclei can be detected if they cross the depletion and neutral region of the diode. The typical detection efficiency can be estimated by the probability that a thermal neutron interacts with a $^{10}$B nucleus. This calculation can be approximated by the amount of $^{10}$B atoms per unit area (average concentration times junction depth is approximately $10^{15}$ cm$^{-2}$ and when multiplied by the capture cross section for the nuclear reaction results in a quantity of the order of $4 \times 10^{-6}$. The nuclear fragments of the reaction will generally be ionized or charged by the passage through the material.

Semiconductor diodes with approximately the same efficiency, but of the $N^+$,P type can be produced by implanting $^{10}$B, (approximately $10^{15}$ nuclei per cm$^2$) in a portion of the oxide layer above the active zone and implanting $^{11}$B nuclei in the field (P) region of the diode to prevent field inversion of the diode.

With respect to generalized alpha particle detector to be used in the detection of thermal neutrons, N-channel dynamic random access memories (DRAMs) can be advantageously used in this application as detectors of alpha particles (and as an indicator of the presence of thermal neutrons), because they can provide an indication of the localized presence of the alpha radiation in space and time. Applicants propose to use the soft error displayed by dynamic RAMs subjected to alpha radiation as discussed in the technical publication by T. May and M. H. Woods *169,* 125 (1980) in order to provide position-sensitive detectors. In order to use these DRAM alpha detectors in a system, apparatus, device or method to detect thermal neutrons, diffusion or implantation with $^{10}$B nuclei or other nuclei with a high thermal neutron capture cross section in the first polysilicon layer of N-channel dynamic RAM memories allows the creation of alpha particles in the first electrically conducting polysilicon layer and subsequent detection because of increased current created in the first polysilicon layer by the above thermal neutron-boron interaction and the presence of the electrically charged alpha particles.

Furthermore, the localization in space and time will generally be returned for use of these above described customized DRAMs (with Boron doped polysilicon layers) as thermal neutron detectors without the generation of unwanted signals which

may occur when a conventional DRAM is used just as an alpha detector and alpha particles cross the bit lines of a DRAM array. Additionally, DRAMs have a very low space-time uncertainty product as compared to scintilation counters, position sensitive, detectors, wire chambers, or bubble chambers. Thus, DRAMs can be directly interfaced with microprocessors or computers for data handling.

It will be clear, as shown in Figure 2, that the use of a thin layer of material doped with appropriate nuclei having a relatively high capture cross section for thermal neutrons such as Boron will permit an alpha particle detector to now detect the presence of thermal neutrons.

For many thermal neutron sources such as reactors, it is necessary to monitor the neutron flux as shown in Figure 3. The monitoring can take the form of an indication of the total flux or can take the form of an identification of an overly large localized neutron flux (that can signify apparatus malfunctions. The devices or apparatus of the instant invention are suited to be placed in an array in the vicinity of the neutron flux source to monitor the strength or to identify selected types of malfunctions. The thermal neutron detectors of this inveniton are relatively inexpensive and relatively light and can be used in an array completely surrounding the neutron source or in a portable array that can be transferred to different locations.

The above description is included to illustrate the operation of the preferred embodiment and is not meant to limit the scope of the invention. The scope of the invention is to be limited only by the following claims. From the above discussion, many variations would be apparent to one skilled in the art that would yet be encompassed by the spirit and scope of the claimed invention.

CLAIMS

1. A semiconductor thermal neutron detector, characterized in that it comprises at least one layer including a high concentration of P type dopant atoms for interacting with thermal neutrons and producing nuclear fragments as well as nuclear fragments detection means associated with said at least one layer.

2. A detector according to claim 1, characterized in that said P type dopant atoms are boron atoms.

3. A detector according to claim 1 and 2, characterized in that said at least one layer is a P type region of a PN diode, and that said nuclear fragment detection means comprises a N type region coupled to said P type region to form a PN diode junction, voltage source means for applying a reverse bias to said diode junction and current detector means coupled to said voltage source means and said N type region for detecting the transfer ionized nuclear reaction fragments across said PN diode junction.

4. A detector according to claims 1 to 3, characterized in that said diode is comprised of silicon.

5. A detector according to claim 1, characterized in that said at least one layer comprises an oxide layer including $^{10}B$ nuclei impurities and being arranged above an active region of an $N^+$,P, diode, wherein the P field region of said diode has $^{11}B$ nuclei.

6. A detector according to claim 1, characterized in that said at least one layer comprises a polysilicon layer including $^{10}B$ atoms of an N-channel, dynamic, random access memory.

7. A device according to claim 1, characterized in that said nuclear fragment detection means comprises means for detecting alpha particles and said at least one layer comprises means for producing alpha particles by an interaction of said thermal neutron with nuclei having a high thermal neutron capture cross section positionate proximate to said detecting means.

8. A detector according to one or more of the preceding claims, characterized in that it comprises an array of semiconductor devices, each device of said array having means for capturing said thermal neutrons and for generating a current resulting from the capture of said thermal neutrons, and sensing means for sensing the current generated by each device of said array resulting from the entering of thermal neutrons into each said device of said array.

9. A method for detecting thermal neutrons, characterized in that it comprises the step of detecting ionized decay products of a nuclear reaction between said thermal neutrons and nuclei with large reaction cross section.

10. A method according to claim 9, characterized in that said decay products result from the nuclear reaction

$$^{10}B + n = {}^{7}Li + a$$

wherein B is boron, n is a thermal neutron, Li is Lithium and *a* is an electrically charged alpha particle.

11. The method according to claim 9, characterized in that it comprises the steps of doping a P-region of a diode with a heavy concentration of boron atoms; reverse-biasing said diode; and detecting decay products caused by said boron atoms capturing and interacting with said thermal neutrons by detecting a current across a junction of said diode.

12. The method according to claim 9, characterized in that it comprises the steps of positioning an array of semiconductor devices having thermal neutron capturing capabilities and a resulting current production indicative of thermal neutron capture near a source of thermal neutrons, and electrically coupling said array to a sensing device for determining the entering of thermal neutrons into at least one of the devices of said array.

13. The method according to claim 12, characterized in that said positioning step includes providing a dynamic random access memory cell array as said array of semiconductor devices, each memory cell of said array having boron atoms located in at least a portion of said memory cell.

14. The method according to claim 12, characterized in that the positioning step includes provid-

ing an array of semiconductor diodes with each device having boron atoms in at least a portion of said device.

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